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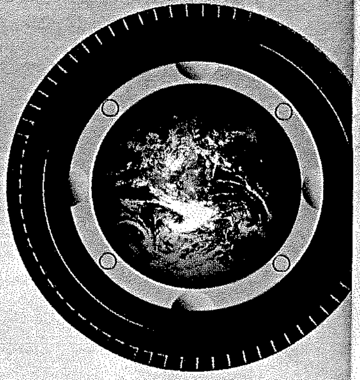

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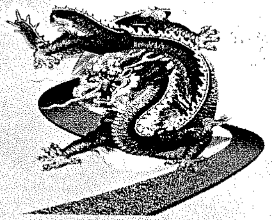

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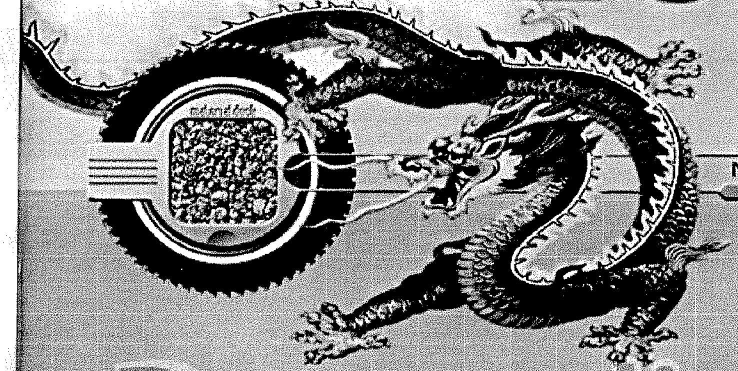

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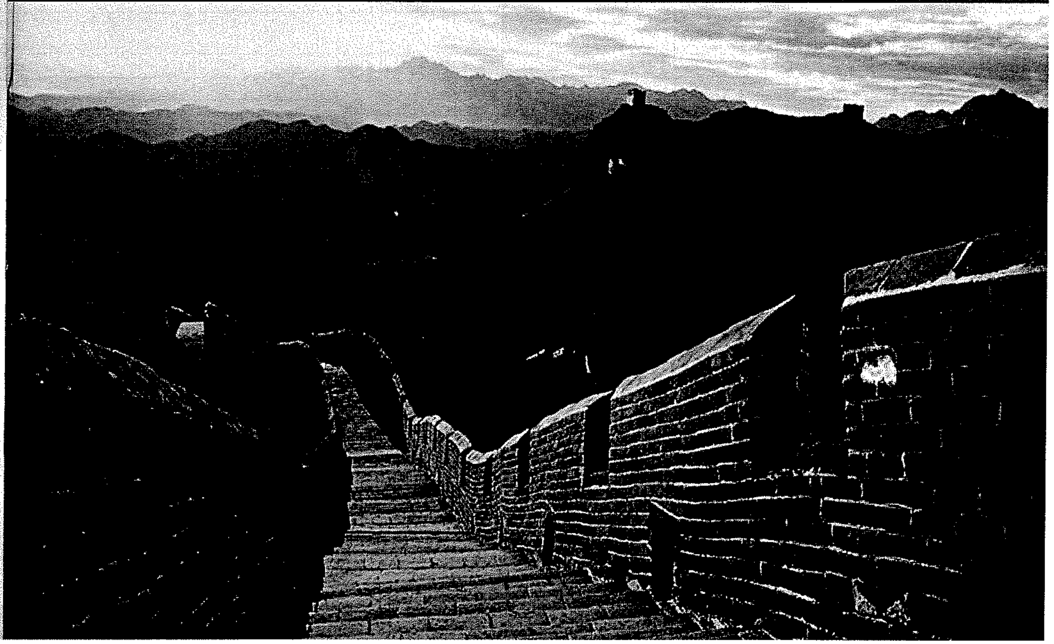

city as well. I sincerely wish every participant a happy stay in Nanjing's golden autumn and the **AR2009** Conference a complete and great success!

Dr. Qian Guochao,
Deputy Director
Jiangsu Provincial Communications Department

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from both processes, cryogenic and ambient grinding, into straight binders improves the mechanical behavior of asphalt hot mixes.

The aging process to which the mixtures were subjected in laboratory produced samples with higher indirect tensile strength. This effect was more pronounced in the mixtures using asphalt binders modified with ambient ground rubber. However, this conclusion cannot be generalized due to the limited number of replicates tested for each mixture condition.

No significant differences were observed in the resilient modulus, the phase angle and the fatigue life when using crumb rubber obtained from the cryogenic process rather than crumb rubber obtained from the ambient grinding process .

The use of crumb rubber obtained from the cryogenic process decreases the resistance to permanent deformation as estimated by the RSST-CH procedure of asphalt rubber hot mixes in relation to the mixtures produced with the crumb rubber obtained from the ambient grinding process.

6. Acknowledgements

This work was part of the doctoral research program at Pos-graduate Program in Geotechnics of the University of Brasilia, with the support of the Department of Civil Engineering of the University of Minho, in Portugal. It was supported with grants from the Brazilian agencies CAPES and CNPQ. The authors are also thankful to the companies that supplied the materials used in this work: Cepsa (supplier of the binders), Biosafe (supplier of the granulated rubber) and Bezerras LTDA (supplier of the mineral aggregates).

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Influence of Digestion Time on the Mechanical Properties of Gap-graded Hot Mixes Produced with Asphalt Rubber Binders

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ABSTRACT: Asphalt rubber binders are produced by mixing crumb rubber obtained from ground used tires with a straight run binder at high temperatures during a period of time named as digestion time. This is one of many variables that influence the physical properties of asphalt rubber produced by wet process. Thus, the objective of this paper is to evaluate how many mechanical properties of gap-graded hot mixes produced with asphalt rubber binder are influenced by the digestion time used to produce this modified binder. The asphalt rubber binders were produced by incorporating 21% in weight of crumb rubber into a straight run binder at 210°C. The digestion times used were 60 and 300 minutes. These asphalt rubber binders were used to produce gap-graded hot mixes which were submitted to tensile strength, fatigue life, resilient modulus and permanent deformation tests. The results show that the increase of digestion time used to produce asphalt rubber binders led to a decrease of tensile strength, resilient modulus and permanent deformation. However, there was a significantly increase of fatigue life of asphalt hot mixes studied.

KEY WORDS: asphalt-rubber, digestion time, gap-graded hot mixes.

1. Introduction

Damages in flexible pavements are generally associated to excessive cracking and rutting in their bituminous wearing courses. The combination of heavy traffic loads and high temperatures is responsible for the premature failure of flexible pavements. This could be mitigated by improving the characteristics of the bituminous material employed in the wearing courses.

The improving of bituminous materials characteristics is generally obtained through the incorporation of different types of modifiers to the straight run binder used to produce the asphalt hot mixes employed in the wearing courses. The modifiers used most often are polymers (SBS, EVA, etc) and crumb rubber obtained from used ground tires. The advantages of crumb rubber from used tires is that it is made by many components (SBR, natural rubber, synthetic rubber, carbon black, etc) that can improve the characteristics of a straight run binder in terms of flexibility and temperature susceptibility.

The product obtained from the mixture of a straight run binder and crumb rubber from ground used tires is named asphalt rubber. This mixture is achieved at high temperatures and during a certain period of time named digestion time. Dantas Neto (2004) showed that the digestion time used to produce asphalt rubber binder by the wet process is one of the many variables that influence the physical properties of asphalt rubber binders. Thus, the objective of this paper is to analyze the effect of digestion time in the mechanical properties of gap-graded asphalt hot mixes produced with these modified binders in the production of asphalt rubber binders.

Three different asphalt hot mixes were studied: a conventional gap-graded asphalt hot mix made with a straight run binder (AC 50/70) and two gap-graded asphalt hot mixes using asphalt rubber binders produced by the wet process with a digestion time of 60 and 300 minutes. The asphalt rubber binders were produced by incorporating 21% in weight of crumb rubber, produced by grinding at ambient temperature, into a straight run binder (AC 50/70) at 210 ℃. The asphalt hot mixes studied were submitted to indirect tensile strength tests, fatigue life and resistance to permanent deformation.

2. Background

According to ASTM D6114/97, asphalt-rubber binders are obtained from a combination of straight asphalt, crumb rubber recycled from used ground tires and other additives when necessary. These additives are normally extender oils used to improve the workability of asphalt rubber or the compatibility between the straight run binder and the used crumb rubber.

The use of binders modified with rubber started in the 1940's. However, only in the 1960's the process of manufacturing of asphalt rubber binders known as wet process or McDonald process was developed and patented by engineer Charles McDonald. Three different processes are used to produce asphalt rubber binders: i) wet process; ii) dry process and iii) the terminal blending (Takallou and Takallou, 2003).

In the wet process, the straight run binder is initially pre-heated to approximately 190℃ in a tank under hermetic conditions and then transported to a blending tank, where crumb rubber is added. The digestion process, which includes the incorporation of rubber in the conventional binder, continues for a period of 1 to 4 hours, at a temperature of 190℃. The process is facilitated by a mechanical agitation produced by a horizontal shaft (Visser, 2000).

In the dry process, particles of crumb rubber are added to preheated mineral aggregates before the addition of the straight bituminous binder (Visser, 2000). In this case, the aggregates are heated to temperatures of approximately 200℃, when crumb rubber is added and mixed for about 15 seconds until obtaining a homogeneous mixture. Straight run binder is then added in a conventional mixing plant.

The time of contact between the rubber and the binder in the dry process is relatively short and not enough to produce all the necessary reactions between the two materials. Therefore, modified mixes rather than modified binders are produced, since there is little digestion of the rubber by the conventional binder.

In the terminal blending process the digestion of crumb rubber into straight run binder occurs at high temperatures. This process has been used in Texas since 1989 and its main characteristic is the use of lower crumb rubber contents than in the wet process (Takallou and Takallou, 2003).

The physical properties of asphalt rubber binders are influenced by the content of crumb rubber, type of crumb rubber, the grain size distribution of crumb rubber, the type of straight run binder, the temperature of digestion, and particularly the digestion time (Anderson *et al.*, 2000; Leite *et al.*, 2000; Dantas Neto, 2004).

Dantas Neto (2004) demonstrated that the digestion time influences significantly the rotational viscosity, the softening point and the resilience of asphalt rubber binders. According to this author, during the manufacturing process of asphalt rubber for a digestion time until 60 minutes, it was observed that there is absorption of light fractions of straight run binder by the crumb rubber particles, what increases the rotational viscosity, the softening point and the resilience of asphalt rubber binders. For digestion times beyond 120 minutes some degradation of the crumb rubber particles occurs, as it may be observed by the decrease of the rotational viscosity and resilience of asphalt rubber binders. The magnitude of these effects depends on the crumb rubber characteristics and on the temperature of digestion employed.

Dantas Neto (2004) also showed that the combination of high temperature and digestion time produce an almost complete degradation of the crumb rubber particles present in asphalt rubber binders. This is more evident for temperatures of digestion around 210℃ and digestion times higher than 300 minutes. Thus, it is expected that these changes in the binder properties also have some effects in the mechanical behavior of asphalt rubber hot mixes.

3. Materials

3.1. Crumb rubber and straight run binder

The crumb rubber used in this work was recycled from ground tires through the ambient grinding process. Approximately 20% of truck tires and 80% of car tires of different types and origins were used in the crumb rubber manufacturing process. The grain size of crumb rubber varied from 0,5 to 2,0 mm. No extender oils were employed.

Table 1 describes the grain size distribution curves for the used crumb rubber and the grading envelope specified by the Arizona Department of Transportation (ADOT). Table 2 presents the results of physical property characterization tests of the conventional binder AC 50/70 used.

Table 1. *Grain size distribution of used crumb rubber and grading envelope specified by the Arizona Department of Transportation (ADOT)*

Sieve size		%Passing		
Inch	**mm**	**ADOT**		**Rubber**
N° 4	4.75	100	100	100
N° 8	2.36	100	100	99.9
N° 10	2.00	100	100	96.8
N° 16	1.18	65	100	47.7
N° 30	0.60	20	100	18.7
N° 50	0.30	0	45	7.5
N°200	0.075	0	5	0

Table 2. *Characterization of the straight run binder AC 50/70*

Physical properties	AC 50/70
Penetration, ASTM D 5-95 (1/10 mm)	52.0
Softening point, ASTM D36-97 (℃)	50.6
Brookfield viscosity at 175℃, ASTM D 4402-87 (cP)	87.5
Resilience, ASTM D5329 (%)	14.0

3.2. Aggregates

The following mineral aggregates were used for producing the asphalt hot mixes studied in this paper:

- Grade 1 crushed granitic stone: particle size 11 - 16 mm;
- Grade 0 crushed granitic stone: particle size 4 - 11 mm;
- Fine crushed granitic aggregate: particle size < 4 mm.

A granitic filler available in the Laboratory of Pavements of the University of Minho in Portugal was also used. The aggregate mixture presents a gap in its gradation curve as specified by ADOT.

Table 3 shows the aggregate mixture composition which complies with the specified grain size distribution. Some results of aggregate characterization tests are also shown. Table 4 presents the grain size distribution of the aggregates used in the asphalt hot mixes and the theoretical values for the designed mixture.

Table 3. *Characterization of aggregates used in the asphalt hot mixes*

Physical properties	Crushed stone 1	Crushed stone 0	Fine aggregate	Filler
Aggregate percentage (%)	31.7	41.7	25.7	1.0
Apparent specific gravity (kN/m³)	26.4	25.8	25.2	25.2
Specific gravity of grains (kN/m³)	26.9	26.8	27.	27.1
Water absorption (%)	0.77	1.39	-	-

Table 4. *Grain size distribution of the aggregates and of the gap-graded mixes*

Sieve size		% Passing						
Inch	**mm**	**ADOT**		**Crushed stone 1**	**Crushed stone 0**	**Fine aggregate**	**Filler**	**Mix**
¾”	19.1	100	100	100	100	100	100	100.0
½”	12.5	90	100	89.55	100	100	100	95.9
3/8”	9.5	79	89	41.02	97.45	100	100	77.9
N° 4	4.8	34	42	3.45	24.57	99.81	100	37.2
N° 10	2.0	15	23	1.09	4.18	76.36	100	22.1
N° 40	0.425	4	14	0.83	2.04	35.04	99.17	10.6
N° 80	0.18	-	-	0.70	1.59	16.56	93.96	-
N° 200	0.075	1	5	0.53	1.13	6.18	75.03	2.8

Figure 1 presents the grain size distribution curves of the specified grade envelope and of the theoretical mixture designed for the asphalt hot mixes according to the aggregate mixture composition described in Table 3.

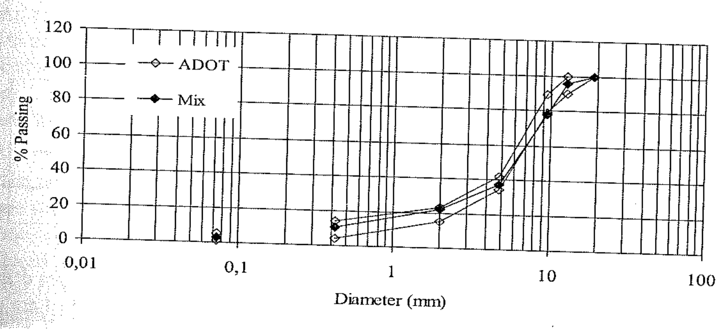

Figure 1. *Grain size distribution curves for gap-graded mixes*

4. Asphalt hot mixes: design and production

4.1. Modified binders used in the asphalt-rubber hot mixes.

The following modified binders were used in the production of studied gap-graded asphalt hot mixes:

- Asphalt rubber 1 (AR-1): straight run binder AC 50/70 + 21% of crumb rubber, digestion time of 60 minutes and digestion temperature of 210℃;
- Asphalt rubber 2 (AR-2): straight run binder AC 50/70 + 21% of crumb rubber, digestion time of 300 minutes and digestion temperature of 210℃;

Hot mixes were also prepared with the straight run binder AC 50/70 in order to compare their mechanical properties with those of the mixes using modified binders. Table 5 presents the physical properties of the modified binders used in the asphalt rubber hot mixes.

Table 5. *Characterization of binders AR-1, AR-2 e AC 50/70*

Physical properties	**AR-1**	**AR-2**	**AC 50/70**
Penetration, ASTM D5 (1/10 mm)	33.5	27.7	52.0
Resilience, ASTM D5329 (%)	58.0	39.0	14.0
Softening point, ASTM D36 (℃)	86.5	89.7	50.6
Brookfield Viscosity at 210℃, ASTM D 4402 (cP)	5680	4280	-

4.2. Design and production of conventional and asphalt rubber hot mixes

The Marshall procedure was used to define the binder content of the studied asphalt hot mixes. Table 6 presents the values of the temperature of the binders, aggregates and compaction of the asphalt hot mixes made with AC 50/70, AR-1 and AR-2 binders. These temperature values were selected by taking into consideration the workability of the asphalt-rubber binders and the experience of local producers in the application of this type of material.

Table 6. *Temperatures used in the production of studied asphalt hot mixes*

Temperatures	AC 50/70	AR1/AR2
Binder heating (℃)	160	170
Aggregates heating (℃)	177	190
Compaction of the mix (℃)	160	164

Table 7 presents all the volumetric parameters for the studied asphalt hot mixes defined in the mix design. All manufacturing conditions of the asphalt hot mixes studied are also presented.

Table 7. *Properties of the gap-graded asphalt hot mixes*

Mix properties	AC 50/70	AR-1/AR-2
Apparent density (g/cm^3)	2.25	2.26
Void content (%)	4.5	4.5
Void in the mineral aggregate – VMA (%)	19.3	17.1
Void filled with asphalt binder – VFA (%)	76.7	74.0
Optimum binder content (%)	7.05	9.0

After the mix design, several specimens of asphalt hot mixes with AC 50/70, AR-1 and AR-2 binders were prepared. A mechanical device with a production capability of 50 kg of asphalt mixture was used to thoroughly mix the mineral aggregates and the asphalt binders. Compaction of the asphalt hot mix was performed in a metallic mould with the following dimensions: 7.3 x 49.2 x 75.2 cm. A vibratory wheel roller was used to achieve the apparent density of the asphalt hot mixes presented in Table 7.

5. Mechanical behavior of asphalt hot mixes: results and discussion

5.1. Indirect tensile strength tests

Indirect tensile strength tests were carried out at a temperature of 20℃ in specimens submitted to an aging process at 85℃ for 5 days in an oven. Non-aged specimens were also tested for comparison. This laboratory aging process is standardised by AASHTO PP2/94 and simulates the long-term aging that occurs in asphalt hot mixes in field. The tests were carried out in accordance with the recommendations of DNER-ME 138/94 standard.

Figure 2 shows the results obtained in the indirect tensile tests for the gap-graded asphalt hot mixes made with AC 50/70, AR-1 and AR-2 binders. The presented labels correspond to the average of values obtained from two tested specimens. These results were submitted to an analysis of variance (ANOVA) using the Statistica 6.0 software, considering 95% as confidence level ($\alpha = 5\%$). The results are presented in Table 8.

An analysis of variance allows defining if there exist differences in the results obtained due to the use of different materials or if they occur due to the variability of the experimental procedures. In this case, if two variables that present different values for indirect tensile strength average are in the same homogeneous group, this difference will be then due to the variability of experimental procedures.

The results presented in Figure 2 and Table 8 show that the aging did not influence the tensile strength of asphalt hot mixes produced with AR-2 (300 minutes), what indicates that the increase in the digestion time improves the resistance of the asphalt rubber hot mixes produced to aging. This can be explained by two factors: i) the hardening produced in the asphalt rubber binder during the manufacturing process of asphalt rubber binder at high temperatures and for a long period of time (300 minutes); ii) the presence of carbon black in the crumb rubber composition. The hardening process occurs by the volatilization of light fractions of the asphalt matrix, as explained in Dantas Neto (2004). Carbon black is an anti-oxidant that decreases the effect of aging over the asphalt binders.

When comparing the asphalt rubber hot mixes tested, it can be observed that the use of a digestion time of 300 minutes produced an increase of the indirect tensile strength in relation to that presented by the asphalt hot mix, the asphalt rubber of which was manufactured using a digestion time of 60 minutes. Again this can be attributed to the hardening of the asphalt matrix produced.

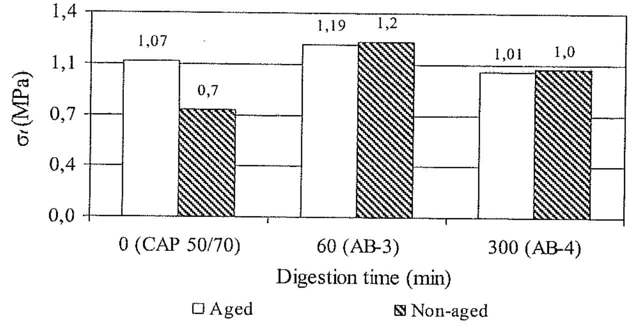

Figure 2. *Indirect tensile strength of the gap-graded asphalt hot mixes*

Table 8. *Homogeneous groups defined from ANOVA on the results of indirect tensile strength tests*

Age S/N	Binder	σt AVERAGE (MPa)	Homogeneous groups										
			1	2	3	4	5	6	7	8	9	10	11
N	AC 50/70	0,73	**										
S	AR-2	1,01			**	**	**						
N	AR-2	1,02			**	**	**						
S	AC 50/70	1,07					**	**	**				
S	AR-1	1,19								**	**	**	
N	AR-1	1,21									**	**	**

5.2. Resilient modulus, phase angle and fatigue life tests

The resilient modulus and fatigue life tests were carried out under controlled strain conditions according to AASHTO TP8/96 standard in beam specimens of bituminous concrete with the following dimensions: 381 ± 6,35 mm in length, 50,8 ± 6,35 mm high and 63,5 ± 6,35 mm wide. Table 9 presents the conditions imposed during the resilient modulus and fatigue life tests. The specimens obtained from asphalt hot mixes made with AC 50/70, AR-1 and AR-2 binders were submitted to the long-term aging process described previously and standardised by AASTHO PP2/94.

Table 9. *Load application conditions for resilient modulus and fatigue life tests*

Test Parameters	Fatigue life	Resilient modulus
Temperature of specimen test (℃)	20	20
Load frequency (Hz)	10	10; 5; 2; 1; 0.5; 0.2; 0.1

Figure 3 presents the results from resilient modulus tests of the specimens obtained from gap-graded asphalt hot mixes with AC 50/70, AR-1 and AR-2 binders. The results show the variation of the resilient modulus with the frequency of load application. Figure 4 presents the results of the phase angle of the asphalt hot mixes studied as a function of the load application frequency.

The results presented in Figure 4 show that the asphalt rubber hot mixes presented higher resilient modulus than the asphalt hot mix produced with AC 50/70. It can also be observed that the use of asphalt rubber binders led to a decrease in the phase angle of asphalt hot mixes. This indicates that asphalt rubber hot mixes present better elastic properties than conventional asphalt hot mixes.

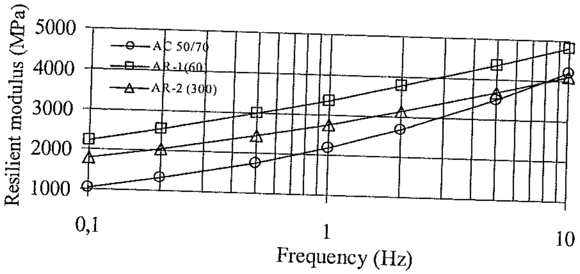

Figure 3. *Resilient modulus of the gap-graded asphalt hot mixes*

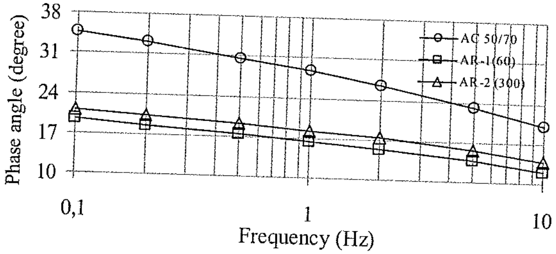

Figure 4. *Phase angles of the gap-graded asphalt hot mixes*

Comparing the results obtained from asphalt rubber hot mixes it can be observed that the increase of digestion time produced a reduction on the values of resilient modulus. This can be related to the degradation process produced on the crumb rubber particles during the manufacturing process of asphalt rubber binders under high temperatures conditions and during long period of time as also verified by Dantas Neto (2004). With the degradation process of crumb rubber some of its synthetic constituents are incorporated in to asphalt matrix improving the visco-elastic properties of asphalt rubber binders and consequently increasing the flexibility of asphalt rubber hot mixes.

Figure 5 presents the results of fatigue life tests of asphalt hot mixes made with AC 50/70, AR-1 and AR-2 binders. Results of fatigue tests show that the use of asphalt rubber binders in asphalt hot mixes produced a significant increase in the fatigue life and consequently in the resistance to cracking of these mixtures. It can be observed that the increase of digestion time used in the manufacturing process produced an additional improvement in the fatigue life of the asphalt hot mixes. The fatigue life of asphalt rubber hot mixes was approximately 3 to 10 times higher in relation to conventional asphalt hot mixes.

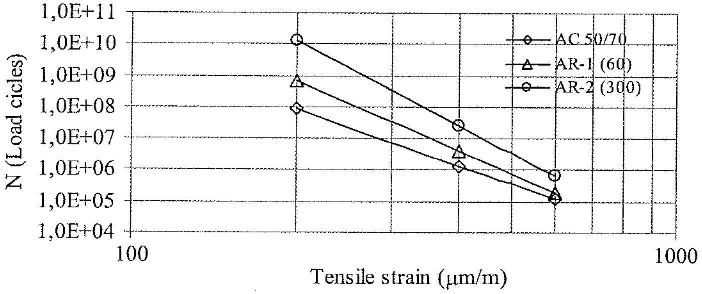

Figure 5. *Fatigue life of gap-graded asphalt hot mixes*

The results of the fatigue life tests show that the possible degradation process occurred with the crumb rubber particles at high temperatures and that the digestion time did not affect the elastic behavior of the binders produced for this research. It is supposed that there is a transfer of elastic characteristics present in the crumb rubber to the asphalt matrix, thus improving significantly its flexibility and elastic properties.

5.3. Permanent deformation of the asphalt hot mixes studied

Sousa *et al.* (1994) considered that rutting in flexible pavements initially occurs due to a densification of the bituminous layers in the first load cycles, and later through the plastic shear strains produced in the bituminous layers. These plastic shear strains cause a displacement of the material of the bituminous layer without a volumetric variation, forming upheaval zones adjacent to the wheel paths.

Based on several works, the Strategic Highway Research Program (SHRP) established a procedure to evaluate rutting in pavements through the evaluation of the evolution of the plastic shear strains that occurs in asphalt hot mixes. The main assumption of this procedure is that rutting is the result of a phenomenon of plastic shear flow under a constant volume of mixture, caused by the shear stress produced below the edge of the truck tires (Sousa *et al.*, 1994).

In this work the resistance to permanent deformation was evaluated by the repeated simple shear test at a constant height (RSST-CH). This test consists of applying to a cylindrical specimen with 15 cm diameter and 5 cm thick a repeated shear stress, while the produced plastic shear strains are measured under controlled temperature.

Table 10 presents the conditions imposed to the specimen during the RSST-CH tests performed. The temperature of 50℃ is typically used for pavements in Portugal, while a higher temperature of 60 ℃ was adopted to simulate more severe climate conditions, as those observed in Brazil.

Table 10. *Test conditions for RSST-CH*

Test Parameters	**Values**
Temperature of the specimens (℃)	50 and 60 ± 0,5
Shear stress actuating on the specimens (kPa)	69 ± 5
Loading time (s)	0.1
Unloading time (s)	0.6

Figure 6 shows the results of the RSST-CH tests for the asphalt hot mixes made with the AC 50/70, AR-1 and AR-2 binders. The results are expressed in terms of number of cycles of the equivalent standard axle (ESALmrd) for the mixture to reach the maximum plastic shear strain or a limit rut depth of 12.7 mm.

The results show that the asphalt rubber hot mixes presented, for both temperatures, were more resistant to permanent deformation than conventional asphalt hot mixes. It can be observed that the increase of digestion time produced a light reduction of the resistance to permanent deformation. Probably this is a consequence of the decrease of the phase angle of the asphalt rubber hot mixes produced with AR-2 in relation to that produced with AR-1, once that the decrease of the phase angle indicates an increase of the viscous component responsible for the mechanical behavior of the asphalt hot mix.

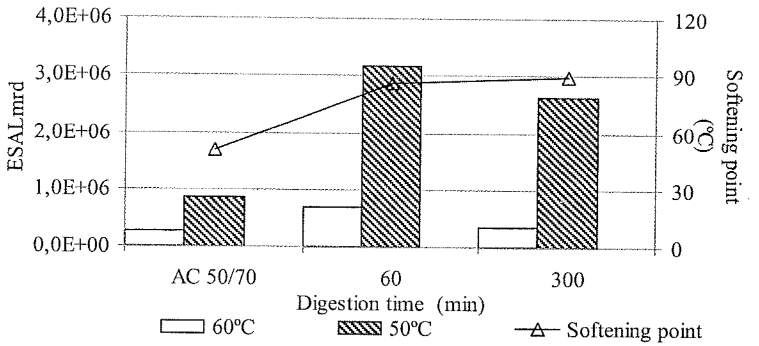

Figure 6. *Results of RSST-CH tests for gap-graded asphalt hot mixes*

5. Conclusions

The results presented in this paper show that the incorporation of crumb rubber into a straight run binder enhanced significantly the mechanical behavior of the asphalt hot mixes. The principal advantages were the increase of indirect tensile strength, fatigue life, flexibility, and resistance to the development of permanent deformations.

The influence of the digestion time on the mechanical behavior of gap-graded asphalt rubber hot mixes was significant. It can be verified that, except for rutting, the use of high temperature and digestion times, within the limits tested herein, improve the mechanical behavior of the asphalt rubber hot mixes produced. The increase in the digestion time can contribute to the production of improved asphalt rubber hot mixes.

6. Acknowledgements

This work was part of the doctoral research program of the Pos-graduate Program in Geotechnics of the University of Brasilia, with support of the Department of Civil Engineering of the University of Minho, in Portugal. It was supported with grants from the Brazilian agencies CAPES and CNPQ. The authors are thankful to the companies that supplied the materials used in this work: Cepsa (supplier of the binders), Biosafe (supplier of the granulated rubber) and Bezerras LTDA (supplier of the mineral aggregates).

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